The Physics of Life. Part II: The Neural Network as an Active Condensed Matter Body

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Nonequilibrium "active agents" establish and break bonds with each other and create an evolving condensed state known as the active matter. Here, the active agents are neurons and the evolving condensed matter is the brain. This paper describes autonomous reconstructions of this active matter. It explains how the neural network creates the mind. The author notices that the active condensed matter made of neurons is similar to that of the molecular bodies of folding proteins and molecular machines, and conjectures that they generate autonomous motions by the same rules. The paper describes voluntary motions of the simple molecular condensed bodies and discusses their interactions with an external environment. In addition to generating motions, the active bodies register external signals and correspondingly adapt their behavior. The active condensed matter bodies can memorize their own active motions and then reproduce those motions. It is shown that deliberate manipulations can transform initially inactive, equilibrated, condensed matter into active matter. Based on this, the author suggests manufacturing artificial animate beings from inanimate matter. These prospective animate forms would be much simpler than real biological organisms. However, they could serve a useful purpose as "generators of autonomous behavior." They would make decisions and solve problems by the same rules as actual neural networks. Therefore, synthetic active condensed matter could produce a basic artificial mind.

Keywords: autonomous biotic motion, active matter, neural networks, physics of mind.

1 Introduction

A neuron is a biological organism that generates its own autonomous actions. In addition, the neuron registers external signals and modifies its actions accordingly; that is, it may act in response to signals. In the neural network of the brain, all these individual organisms unite into a single large entity and form a collective organism with new autonomous behavior. This paper explains how a collection of simpler organisms creates a collective organism. It also describes the characteristic behavior of the neural collective organism.

In Part 1 of this paper, I defined the individual living organism as an active condensed matter body. It is a piece of structurally arranged, condensed matter that implements a spontaneous reconstruction. The reconstruction may involve simultaneous and sequential events. In a single organism, all of these events are connected, such as by cause-and-effect relations. The reconstruction is driven by special structural elements of the condensed matter that undergo chemical transformations. The chemical transformations do not conserve the volume of the structural elements. Therefore, they move the condensed body and alter its structure. In particular, they alter the bonds among the elements. These transforming structural elements of condensed matter were termed "active agents."

The collective organism arises when simple organisms join their material bodies into a large, common, active condensed matter body (Fig. 1). In this common material body, all the individual reconstructions join together and create a common coordinated reconstruction. In the collective organism, the local reconstructions corresponding to the previously autonomous organisms become the interdependent components of this larger reconstruction.

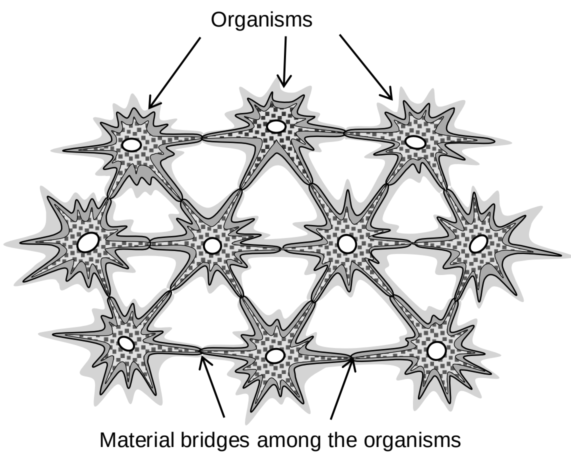

Fig. 1. Condensed matter made of living organisms. The organisms have material bonds with one another.

The neural network carries out a special collective reconstruction, which may be described as follows.

In the neural network, the neurons periodically establish new—and break old—material bonds with one another. Physically, all the neurons stay in their original locations, yet their connections become "rewired." This implies that the neurons rearrange with respect to one another; they undergo permutations.

Each configuration of the neurons corresponds to a particular, unique collective reconstruction. In each configuration, the neural network performs a distinct task. Every permutation of the neurons changes the structure of the collective reconstruction; the collective organism begins to function differently. The rewiring continues.

Correspondingly, the neural collective organism changes its own structure, like a kaleidoscope pattern. Because the number of different neural configurations is colossal, the brain can perform an immense variety of different actions.

Regardless of its incredible versatility, the reconstructing neural matter never evolves beyond recognition. Periodically, it returns to a certain "original" configuration. Moreover, the neural condensed matter tends to execute repeating sequences of actions or daily routines because, during every permutation, the major part of the neural connections remains unchanged. The reconstructing neural matter also can evolve. It can learn and perform increasingly complex actions. This implies that the neurons can grow completely new bonds and invent new ways of connecting to one another. I will address these effects later.

My more immediate goal is to answer a more important question: What controls the reconnections of the neurons? To create rational behavior, the reconstructions of the neural matter must be deliberate; they cannot be random or chaotic.

2 Evolving connections among communicating organisms

I will first explain why, in general, simple organisms tend to connect to one another and create coordinated groups, such as complex organisms. The answer to this fundamental question may come from condensed matter physics. Part 1 of this paper argued that any living organism implements the process of chemical condensation. It builds the missing chemical bonds among its parts. When living organisms seek to bond with one another, they simply continue the condensation process. The resulting complex organism is a larger condensed matter body with a larger reconstruction.

A larger reconstruction should have a faster metabolism. However, not all organisms unite when they meet. Usually, they strive to stand apart. This happens because their reconstructions destroy one another; they are incompatible. The conflicting organisms would get rid of the destructive bonds and even create protective barriers from one another.

In rare cases, the reconstructions of different organisms construct one another, or "cooperate." Such cooperation manifests as the mutual enhancement of the organisms' metabolisms. The compatible organisms may create a common reconstruction.

Organisms partially destruct and partially construct one another on a regular basis, attaching the compatible parts of their reconstructions and detaching the incompatible parts. As a result, they produce a collective reconstruction, as illustrated in Fig. 2.

The story does not end there. Every organism is an evolving system. It goes through different stages of its life cycle (or daily routine) and periodically changes its occupation. At different moments, the same bond among organisms may transmit either constructive or destructive influences. For this reason, the bonds among organisms must be constantly rewired; the connections that become destructive must be quickly eliminated, and new, constructive connections must be installed instead.

Two communicating organisms should create a quickly evolving system, as shown in Fig. 2. They periodically establish new connections and break old connections with one another. If the organisms' metabolisms cycle periodically, then the connections among them should cycle with a common period.

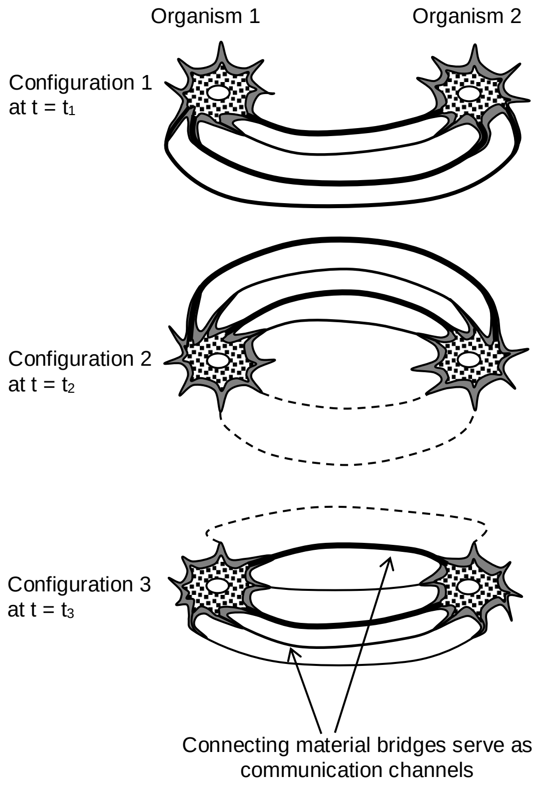

Fig. 2. The evolving condensed matter made of two organisms and their communication channels (material bridges). At different times the material connections are different.

Surely, not all cellular organisms are capable of accomplishing such difficult manipulations as periodic reconnections. For this reason, creation of complex multicellular organisms is rare. Apparently, neurons are exceptionally good at reconnecting. Thanks to this remarkable capability, they showcase the proper collective reconstruction.

3 Establishing connections among organisms

Establishing a new bond (or breaking the existing bond) among organisms is not an instantaneous event. It is a long process that requires gradual adjustments of the organisms' metabolisms as well as structural alterations of the material bridges that link the organisms.

Fig. 3 shows two organisms that come into contact via a material bridge. The active reconstruction of the first organism strives to move and rearrange the second organism.

For simplicity, let us assume that these interventions are purely mechanical, that is, the first organism attempts to perform transmutations of the atoms or the atomic clusters in the bridge and in the second organism. The bridge and the second organism resist the rearranging. Additionally, they hinder movements and reconstructions in the first organism.

Occasionally, the second organism yields and allows a rearrangement. This implies that the first organism transmitted information to the second organism. In the condensed matter, the ordered reconstructions, such as transmutations of the atoms, encode information. The transmission of the reconstruction from the generator of the reconstruction (the source) to the recipient is the act of communication.

In the recipient organism, the assimilated signal may stimulate the response reconstruction. The two organisms could then create a feedback loop with positive reinforcement.

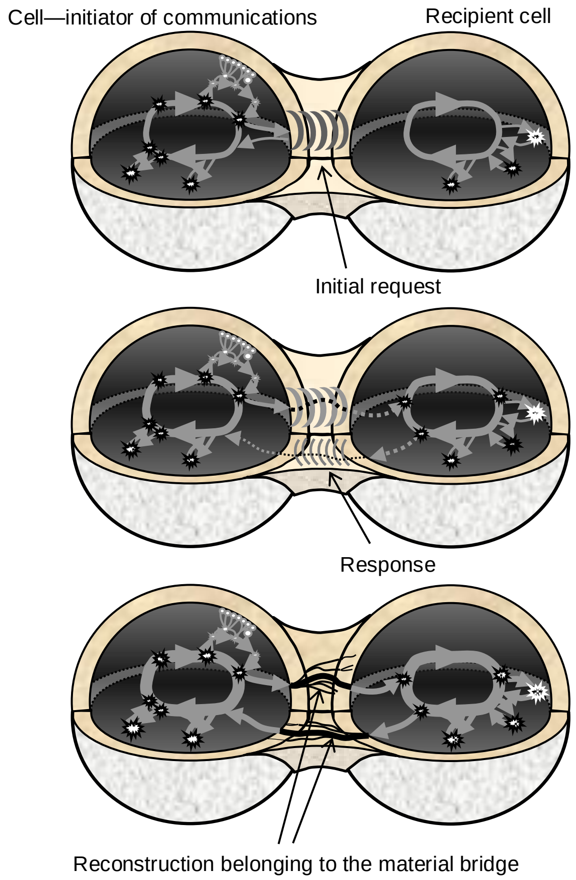

Fig. 3. The cell on the left attempts to connect to the cell on the right. After establishing communications, metabolisms of both cells are enhanced.

The mechanical motions with increasing amplitude will eventually rearrange and soften the material bridge. The initial, isolating barrier between the independent organisms would then become apt to transmit particular types of mechanical motions.

The connections among actual neurons must be established in a similar fashion. They must be reinforced by the transmitted communications; the intensified communication among cooperating neurons should strengthen the bonds and increase their carrying capacity. If the neurons fight, the corresponding destructive signals must eliminate the bond. The decision to produce a connection is made by both neurons, taking into consideration the compliance of the material bridge.

4 Trial-and-error reconnections in the neural network

Let us first assume that the neurons grow new bonds completely at random. During communications, the neurons would determine whether those connections were constructive or destructive. They would retain the useful connections and dispose of the detrimental ones.

This trial-and-error method could work well for small neural nets consisting of several dozen neurons. However, when the number of neurons increases, and the number of links among the neurons increases proportionally, the whole system would halt.

In large neural nets, the number of random trials required to achieve a viable neural arrangement grows dramatically. It requires more resources and more time. The probability of finding an appropriate configuration in a reasonable time diminishes drastically with the growing number of neurons.

The neural network must be able to quickly adapt to the changing environmental conditions, and trial-and-error adaptations would be completely inadequate for this purpose. Brains comprising billions of neurons quickly adapt, and one is compelled to conclude that the neurons do not reconnect at random. Instead, they must follow specific instructions coming from all the other neurons.

5 Subordination in the collective organism

Indeed, in addition to reconnecting, the neurons exchange information signals. Let us consider the neural network sketched in Fig. 2.

With regard to subordination, the communicating organisms have a dual nature. On the one hand, they partially obey one another; on the other hand, they retain partial independence from one another. Subordination relates to the way the organisms generate commands.

When the organism creates a reconstruction, it generates information, and it uses its own chemical resources for that purpose. The active agents undergo chemical transformations and convert hidden chemical energy and order into the observable mechanical motions and structural alterations.

A certain fraction of the chemically transforming agents within the communicating organisms is activated by the common part of the reconstruction. Another fraction of the agents is activated by the organisms’ unshared part of the reconstruction. This independent generation of the

commanding signals implies partial independence of the organisms.

There is one important special occasion. The common part of the reconstruction may effectively inhibit the independent actions of the organisms, and the organisms may completely lose their independence. In such a case, the communicating organisms will become a truly collective organism. The common reconstruction that effectively suppresses independent actions of the organisms creates the collective, enslaving agent.

An analogous effect should take place in the neural network of the brain. There, any given neuron should never excite of its own free will; it may do so only with the collective permission of all the other neurons. The common reconstruction of the neurons that inhibits or excites the actions of the neurons will be the controlling entity—it could be called the “collective free will” of the neural network. The next section explains how this entity emerges.

6 The collective free will of the neural matter

Here, I will make a very simple but important conjecture. I will assume that the neurons in the neural networks can relay received signals to other neurons. Then, in a highly interconnected neural network, the signal from any given neuron to another will travel along many different paths, including the paths that go through other, intermediate neurons (Fig. 4). While traveling along the neural network, the signal exchanges information with the intermediate neurons. It activates or inhibits them, and changes their intention to reconnect or implement a personal reconstruction. In turn, the neurons alter the signal and mix the signals that come from different sources.

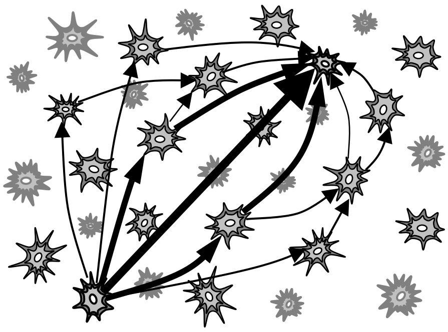

Fig. 4. Two neurons connected via multiple paths.

In the condensed matter made of neurons, all the information signals generated by different neurons mix and connect to one another. They form a common entity that could be regarded as condensed matter made of signals, or the “collective signal.” The collective signal comprises a vast number of different components that affect one another, and it occupies the complete body of the neural network. The neurons constantly produce and absorb new signals. Consequently, the collective signal quickly evolves, by accepting and surrendering components (Fig. 5).

The collective signal and the neurons make a special active agent, which I will call the “collective active agent.” Indeed, it is the structural element of matter that undergoes autonomous transformations. However, this collective active agent is delocalized, it occupies the entire volume of the neural condensed matter body, and it generates the total reconstruction of the whole neural condensed matter. The collective agent has collective free will.

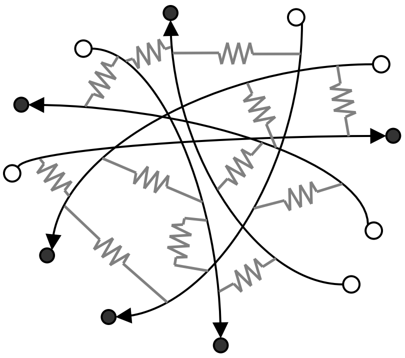

Fig. 5. The connected signals create a condensed matter made of signals. The links between the signals are represented by springs. These links also change over time.

This section has articulated the first key idea of this paper: In the relevant neural networks, the signals are not isolated from one another. Instead, they unite into a single entity and create an evolving condensed state. Behavior of the neural network is governed by the evolution of this condensed signal.

The second key idea of the manuscript will be stated in the next section.

7 Collective reconstructions of highly interconnected neural matter

Actual neural networks have a very distinct feature: they comprise a very large number of bonds among neurons. For example, one neuron in a human brain may be simultaneously connected to up to ten thousand other neurons [1].

A growing number of bonds corresponds to further condensation of the neural matter and might profoundly affect the behavior of the neural matter.

When the number of bonds among the neurons increases, the neurons start receiving many contradictory requests and become increasingly frustrated. This will inhibit the neurons’ activities and hinder their reconstructions. The growing number of bonds brings about an effect similar to the transition of matter into a different aggregate state: the matter transits from an agile, loose state to a state reminiscent of a solid. Nevertheless, the activities of the neurons are not entirely inhibited. Therefore, this solid-like active matter still performs some constrained autonomous reconstructions.

The growing number of bonds greatly increases the number of causal links among different events in the neural matter. Any particular cause acquires multiple consequences.

Likewise, any consequence has multiple causes. It becomes impossible to tell the important from the insignificant causes. At first glance, the overwhelming number of cause-and-effect relations seems to make the description of this evolving system very difficult. In reality, however, plentiful constraints significantly degenerate and simplify motions of the active condensed matter in this solid-like aggregate state.

The reconnections of neurons in this solid-like active condensed matter may be illustrated as follows: In the highly interconnected neural matter, breaking of one bond between neurons drags the matter and causes the breaking of another bond. Instead of individual bond reconnections, the condensed neural matter will produce extended ruptures in a process reminiscent of the propagation of cracks in solid matter. Similarly, the extended ruptures close like the fastening of a zipper: restoration of one bond pulls the matter and recovers the next bonds.

The base operating principle of the neural matter holds. It involves the regular exchange of signals among neurons and periodic reconnections of the bonds because of the changing cooperative conditions. This time, however, the reconnecting becomes a collective effect. The decision about the rewiring of a given neuron is strongly affected by the collective agent.

This brings about a profound change in the abilities of the neural matter. The collective agent now can coerce the disagreeing neurons into performing actions that they do not want to perform. Moreover, the collective agent can incite permanent structural modifications in the neurons. The neurons will undergo “conversion training” under the influence of the collective reconstruction of the active condensed body. The neural matter as a whole acquires the ability to memorize its collective actions and then reproduce those actions.

8 The mind and its actions

The condensed matter made of the highly interconnected neurons reconstructs itself as follows: Instead of individual reconnections of neurons, it spontaneously produces an extended rupture, rearranges itself, and then closes the rupture and restores the bonds. It does this of its own free will. Additionally, the decision to undertake a collective reconstruction can be affected by some external influences.

In the jammed neural matter, the rupture produces a region with the fewest constraining bonds among the neurons. Consequently, most of the transformations will be localized in the area of the rupture.

One should assume that the neural matter is somehow organized and ordered; thus, the action produced by the ordered rupturing also will be organized and ordered. In this coordinated action, all the participating neurons will act jointly, as a coordinated team, and all the elements of the extended action will be linked by cause-and-effect relations.

A picture is beginning to emerge: The collective agent of the neural matter initiates and terminates ordered, coordinated actions and controls their courses. It makes the decisions on which particular action to perform in the current circumstances. This collective active agent could be regarded as the “mind” of the neural network. I define the mind as a living collective entity with certain characteristic behavior. It registers large quantities of external stimuli and perceives them as a coherent picture. Most of the time, the mind suppresses its own willed actions and responses. Occasionally, however, it will become excited and perform a particular coordinated action. Then, of its own volition, it will return to the initial quiet state.

I have so far briefly described my conjectures regarding the neural networks’ principles of operation. I now will proceed to more detailed explanations. Toward the end of the paper, I will make an important assertion: The solid-like, jammed neural matter can be replaced with a particular artificial substitute. This substitute will employ solid-like active condensed matter made of atoms that reconstructs itself through self-rupture and reconnection.

9 Mechanism of the spontaneous rupturing

In the quiet state, numerous constraints suppress the collective active agent’s activity. Nevertheless, the neurons belonging to the collective agent are not dead; they produce some restrained reconstructions and accumulate energy. Additionally, the collective agent is affected by an abundance of external signals.

These internal and external influences may produce fluctuations in the density of bonds, and the neural matter may produce a small hole in itself. The removal of the constraints in the local area of the neural matter awakens some of the inhibited neurons. It must be noted that the excited neurons are scattered everywhere across the neural body. This happens because the local rupture is connected to all localities of the well-interconnected neural matter (Fig. 6).

Generally, different neurons in different locations within the network have different intentions. Some of the excited neurons want to close the rupture by rebuilding the missing bonds. Other neurons want to expand the rupture by breaking some excessive (for them) bonds. In order to do anything with the rupture, different parts of the collective active agent must reach a consensus. The reconstruction that takes place around the rupture should coerce the disagreeing minority into cooperating.

Suppose that the majority of the neurons wants to break the bonds and succeeds in subduing the will of the disagreeing minority. In this case, the rupturing and excitation of the neurons engage in mutual stimulation. The rupture expands in an avalanche-like fashion. This process is analogous to breaking a dam with the flow of water: the active motion breaks the constraining barriers and expands the breach [2]. (In the case of a dam breach, however, all the different parts of the water basin want the same thing—they aim to fall down. The neural matter is different. There, the different parts of the flow may want to go in different directions. The majority must entice the flow to propagate in one direction.)

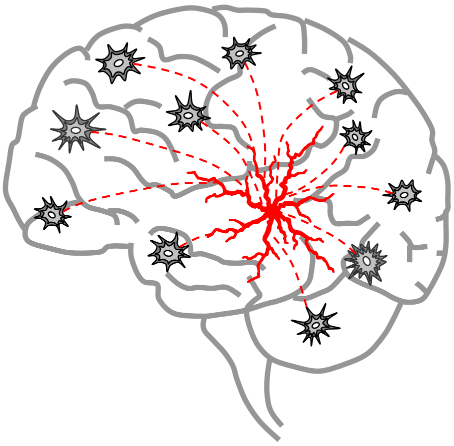

Fig. 6. The neurons connected to the rupture may belong to different, distant parts of the brain.

The neurons need to maintain a particular number of connections. Neurons that lose too many bonds change their intentions; instead of breaking the bonds, they begin to form new bonds. At this moment, the collective agent changes its intention and makes the decision to terminate the rupturing. The neural body closes the tear and returns to the quiet state.

The rupture plays an important role in the constrained neural network. It connects all distant parts of the network and offers them a ground for negotiation. It becomes a place and means for converting disagreeing neurons. The decisions to start or terminate the action are made by the reconciled mind.

10 Evolution of the collective signal during rupturing

In the quiet state, all the components of the collective signal are strongly connected or "glued" together. In other words, the condensed matter made of signals resembles a solid. Consequently, the amplitudes of the (contradicting) signals are very small. Communications among different parts of the neural network are inhibited.

The localized rupture decreases the number of constraining links between the components of the collective signal. The avalanche-like expansion of the tear may trigger a "phase transition," in which the condensed matter made of signals will transit from the solid-like state to a more loose state. The collective signal will separate into the less connected pieces. This will facilitate exchanges of information among different parts of the neural network.

Because of the high interconnectivity, the localized rupture unleashes communications across the whole neural network. The neurons across the network will work faster and generate more signal. The larger the size of the rupture, the stronger is the excitation of the collective active agent.

11 Evolution of neural matter during rupturing

The impact of the rupture on the neural net is illustrated in Fig. 7. There, the highly interconnected neural network consists of only two neurons. In the quiet state, the neurons are connected via a "gray mass" of numerous faint signals. All these signals may contradict one another. They are connected to one another and for this reason are very weak. They inhibit both neurons.

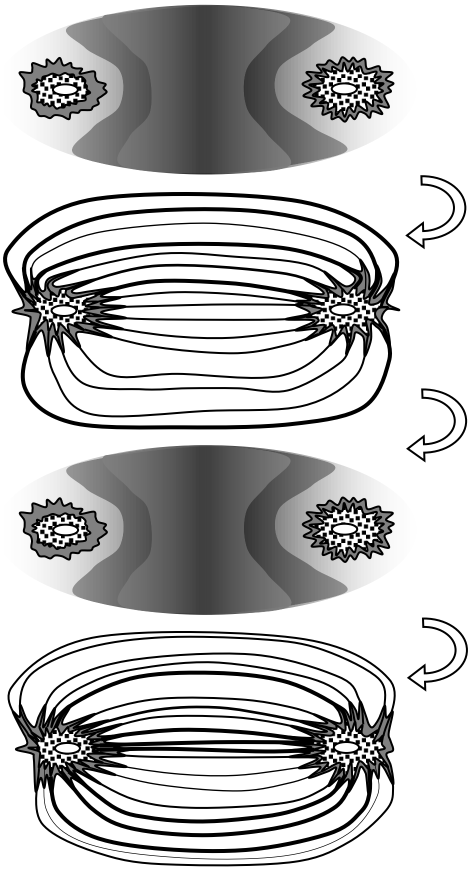

Fig. 7. Separation of the collective signal during the rupture. The neurons enhance the cooperating links and eliminate the obstructing links. Equivalently, the neurons arrange into an ordered pattern and perform a large, collective reconstruction.

During the spontaneous rupturing, this weak and disordered collective signal separates into organized components. The destructive signals are eliminated and the constructive signals get enhanced. The "gray mass" made of signals becomes black and white.

At this moment, both neurons boost their activity. They create a firm common reconstruction and execute a certain collective action.

After the collective action is completed, the neurons decrease their activity, the communications between the neurons subside, and the signals stick together. Once again, the signals form the "gray," interconnected, condensed state. The whole system returns to the quiet state. After a while, the system may spontaneously divide again. However, this could be a completely different rupture; the neurons will be reconnected in a different fashion and thus will perform a completely different collective action.

12 Desires

I now turn to an explanation of how the collective agent decides the manner in which it will rip the neural body and construct a particular collective action. My conjecture is that the neural condensed matter is guided by its own desires.

A special characteristic could be assigned to the neurons: the desire to perform a certain individual action. For instance, a neuron may acquire a desire to grow a new material bond or to send a signal. Most such desires remain unfulfilled because the neurons are obstructed by the neural condensed matter, and the unfulfilled desires get subdued. On rare occasions, when the neurons get unlocked, their desires reemerge. In the yielding environment, the desire grows during performance of the action. When the neuron satisfies its needs and depletes its energy, the desire disappears.

The collective agent communicates with every local neuron. If both the collective agent and the local correspondent satisfy their desires, the communication proceeds with positive feedback, and these actions gain strength. Otherwise, they are curtailed.

Building the bonds is hard work, and the neurons must spend substantial energy for that purpose. Overall, this process is equivalent to surmounting obstacles or forcefully breaching a barrier. Additionally, the disagreeing neurons must be coerced into cooperation. Therefore, in addition to the desires, the collective organism has strong reluctance or unwillingness to perform any action. It should not be forgotten that the condensed body has many neurons that want to heal any possible rupture and stop any active process. Any activity always battles with the desire of the neural body to inhibit any active process.

13 Principles of decision making

Taking into consideration all of the above, one could formulate the general principles of decision making. The collective agent will undertake its next action according to the following rules.

Above all, it will choose the action that it is the least reluctant to perform. This is the action that is least prohibited. Simultaneously, it will choose the most desired action. Therefore, the collective agent will elaborate a compromise between the path of least resistance and the greatest satisfaction. Intrinsic desires may be triggered by external influences. The collective agent also may have to react to the most urgent external call.

During the generation of sequences of actions, the collective agent will first pick the actions that require the smallest investment of energy and that produce the fastest positive results. After the easiest options are expended, it will switch to progressively more difficult actions. Evidently, the collective agent's behavior is rather sound and reasonable.

If the collective agent had to choose between several alternative actions, it would choose the action with the greatest positive feedback (provided that this action inhibits its competitors most efficiently). If two local actions were in conflict with each other, the one that grows faster would win and the other would get inhibited. If, instead of competing, two actions cooperate, they will be executed simultaneously, creating a complex coordinated action. (Such complex actions arise when different "body parts" of the active condensed body move simultaneously in a coordinated fashion.) During execution of a particular action, as soon as the positive feedback declines and an alternative action starts producing a greater satisfaction, the collective agent "loses interest" in the initial action and switches to the new task.

The collective agent has a strong desire to terminate any action during its execution. When the action starts to bring back a lesser satisfaction, the desire to stop will win. The collective agent may abandon the action, leaving it unfinished, and progress to another, more satisfying or urgent action, though it may return to the abandoned action at a later time.

14 Predicting the observable behavior of the collective agent

Predicting the next decision of a collective agent would require exhaustive knowledge about all the current active processes, desires, barriers, and causal relations. This problem is unsolvable by any known means; even the smallest neural networks include too many elements, and the system comprises an unmanageable number of changing parameters. In addition, these systems do not allow any reduction of variables—any particular event or causal relation may be important in determining all subsequent events.

Only the neural condensed matter body itself may resolve this problem, exclusively by executing the action. The collective agent itself cannot predict its own actions. Through its own reconstruction, it "calculates" only the immediate next step.

However, there is a special kind of the active condensed matter for which behavior could be predicted. Those predictions are not calculated. Instead, they are derived from empirical observation of the earlier decisions of the active condensed matter.

This possibility is based on a particular property of active condensed matter: reconstructions of the matter do not transform its structure beyond recognition. Instead, during the reconstruction, the condensed matter brings itself into a configuration that is very similar to its initial state. Consequently, the active matter can repeat similar actions multiple times. Part 1 of this paper called these configurations "recurring states."

To produce recurring reconstructions, the active condensed matter must have a specific composition and a specific turnover of the desires of the active agents. In essence, the active matter must contain multiple equivalent elements that can perform equivalent tasks. For instance, the neural network must contain multiple interchangeable neurons. The work of only one of these neurons should suffice for the execution of a particular action. After executing the action,

the used active agents should be replaced by equivalent fresh agents with similar desires. The reader is referred to Part 1 for details.

Any biological condensed matter has this important property. Thanks to this quality, real organisms have stable structures that they retain throughout their life span. The following description sticks to that particular case.

15 Complex predictable actions

Let us consider very well-ordered neural condensed matter in which the neurons are arranged in an ultimately precise order. This well-arranged neural matter is deliberately streaked with “easy-tear” lines, and the active body will prefer to rupture along these lines. Every easy-tear line produces a particular rupture and realizes a specific ordered collective action (Fig. 8).

In some measure, knowledge about the existing easy-tear lines enables an external observer to predict the actions of the active neural matter. However, the internal desires of the neurons would remain unknown, and therefore the external observer will never be able predict decisions to a certainty. Nonetheless, he will know the list of available actions from which the collective organism can choose.

The size of the rupture determines the scope of the action. In a well-arranged and well-segmented active condensed body, the scope of the action could be quite large. During such actions, many parts of the cerebral neural matter become excited and actuate multiple body parts in full coordination.

The neural body also may be strongly entangled (disordered) and contain no lengthy easy-tear lines. In this case, it would produce only small ruptures, and the neural body would execute a series of more constrained, less graceful actions. Moreover, the entanglement of the neural condensed matter could be so strong that the neural body would be able to produce only very primitive actions.

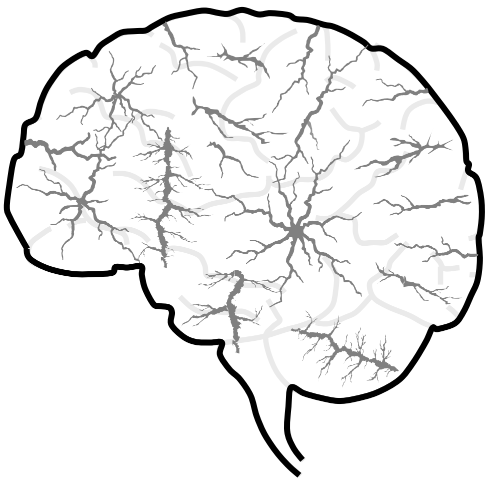

Fig. 8. Easy-tear lines. The neural matter may rupture in several alternative ways. Every unique rupture corresponds to a particular ordered collective reconstruction.

16 Disentanglement of the entangled neural matter and production of more complex actions

The entangled neural matter may get sophisticated and extend, diversify, and develop its actions. The disentanglement is done by practicing, that is, by repeating the actions many times. This important ability is based on two characteristics: the ability of the neural matter to memorize actions, and its ability to extend the tear lines. In other words, the recurring states are not completely recurring. They slowly evolve through repetition, as I will explain.

After an “easy-tear line action” is finished, the rupture gets healed. However, the restored bonds differ from the original ones because the neurons become rearranged during the action. This remains true even for recurring actions; they differ to some small extent.

In particular, the action may weaken the stitches that close the easy-tear line, increasing the chances that this tear will be repeated in the future. In other words, the executed actions would be memorized by the matter.

In addition, the actions also may extend and become more complex, because the tear lines may grow in size. This effect is similar to the breaking of a river dam by flowing water—the flow through the rupture may expand it.

Multiple repetitions of similar active processes will rearrange, order, and segment the condensed body. This disentanglement could proceed without any external intervention. In such a case, this corresponds to self-learning. However, finding a good new rupture and creating a new easy-tear line (i.e., inventing a new useful skill) is very difficult. It requires multiple unsuccessful tries, and it might consume a great deal of time and energy. The most effective disentanglement requires the guidance of an external trainer. This would involve repeated reward–penalty communications and the development of complex skills from simpler ones.

When the condensed body acquires partitions by means of the easy-tear lines, the cause-and-effect links among different events decrease in number. The disentanglement separates the events into related and unrelated ones. There will be important and unimportant causes and effects. There will be essential and insignificant processes.

17 Recognition as a complex action

Let us consider interactions of the disentangled neural organism with an external environment. The active neural matter body may assimilate a whole collection of external influences and produce one large, integrated rupture in response. Then it is possible to say that the active neural matter body perceived these external influences as one complex signal in which all of the components were connected to one another. That is recognition. The complex disentangled organism thus has a fundamental ability: it can recognize and assimilate complex information.

Very often, however, the structure of an active condensed body does not allow recognition of excessively complex signals. Correspondingly, the active body will be unable to react to them in a complex way. In such a case, the reaction of the active body will be separated into a series of simpler ruptures or recognition events. During each event, the body will assimilate only a fraction of the complex information and generate a certain response. Recognition and assimilation of information sequentially, in small portions, is very typical of living organisms in general. Very often, the process of assimilation implies bilateral communication with the external correspondent.

Assimilation of complex information requires adaptations. Those are slight modifications of ready-to-execute actions. Receiving the exact signals that would ideally match the easy-tear lines of the condensed matter body is unlikely. In order to perceive the complex signal, the body must slightly alter its rupture pattern. The simpler the conveyed message, the easier it is to digest.

Bilateral communications with the outside world stimulate the disentanglement described in the previous section. Thanks to this process, the neural body elaborates new advantageous responses to the previously unknown signals. This process might be understood as problem solving. After the appropriate response is elaborated, the neural condensed matter body tends to reproduce it automatically, though it may adapt it slightly to suit the current circumstances.

A particularly strong external influence may coerce the entire organism into executing an action that it does not want to perform, or it may restructure the body of the organism using brute force. This happens, for instance, when a new and entangled condensed matter body encounters a particularly strong signal that it cannot assimilate. In this case, the overpowering external forces would make absolutely new tears in the body. The condensed matter body would resist as much as possible, but this violent event could destroy the body, killing it. Alternatively, if the tears could be healed and the body could regain its operability, the body would learn completely new skills.

18 The atomic counterpart of neural condensed matter

This section, which begins the concluding part of the manuscript, addresses the topic that was announced in the abstract: that neural condensed matter may have a simpler natural counterpart.

Reconstructions of the neural condensed matter might be compared to the spontaneous reconstructions of the subatomic protein bodies and molecular machines [3]. A molecular machine is a piece of atomic condensed matter that tends to condensate (establish missing chemical bonds among its atoms) or decondensate (remove excessive chemical bonds from among its atoms). In this respect, its atoms (or its atomic clusters) are the active agents that emulate the desires of the neurons. This condensed matter has a significant number of already existing chemical bonds; those constrain further reconstructions of the condensed body. One might say that the constrained body of a molecular machine is in a distinct aggregate state of matter. On the one hand, it approaches the solid state; and on the other hand, it still reconstructs. The amplitudes of these reconstructions are very small. At any given moment, the majority of the possible active agents remains strongly inhibited.

The atomic condensed matter of the molecular machine could be heterogeneous, and it could be prone to condensation and decondensation simultaneously. For this quality, it should contain different atomic clusters, some that want to establish bonds and others that want to break bonds with other clusters. Then, this matter will exhibit behavior similar to that of the neural matter. Intermittently, it would spontaneously escape from the constrained quiet state, become excited, and perform a significant rearranging. Then, on its own volition, it would return to the quiet state.

The spontaneous self-excitations emerge when some of the active agents establish positive feedback communications with other agents. Mutual stimulation enhances the amplitudes of the atomic rearrangements. These rearrangements destabilize and loosen the condensed body; they rupture the matter. The ruptures eliminate constraints and remove inhibition from some additional agents. Thus, the ruptures and the active agents engage in mutual stimulation. This mutual stimulation is comparable to the breaking of a dam by a flow of water.

The ruptures destroy the internal bonds, resulting in de facto decondensation. When the number of broken bonds rises above a certain value, the body becomes overwhelmed by the desire to condense and restore the bonds. At this stage, the active body stops rupturing, closes the holes in itself, and returns to the quiet state. The burst of activity associated with the rupturing registers as a distinct voluntary motion of the active condensed body.

The corresponding reconstruction is illustrated in Fig. 9. During the burst of activity, the active condensed body spontaneously produces and widens a hole in itself. It then fills the created hole with new material. One could say that the body partially turns itself inside out through this hole. During this motion, the rupture shrinks and closes. Then the hole is restitched with new material bonds.

At the site of the healed rupture, the restored bonds may become stronger or more numerous than the original bonds. The total transformation would then correspond to condensation of the body. Alternatively, the bonds may become weaker or less numerous than the original ones. This would yield decondensation of the body. In either case, the condensed body will retain the memory of its active reconstructions. If the body produces similar (recurring) reconstructions, these changes will accumulate. Generally, the reconstructions will disentangle the matter, as we will see in Section 20.

Fig. 9. Spontaneous opening and growth of the internal tear in the condensed matter. The open tear is filled with an alternative material.

19 Signaling in the atomic active condensed matter

I argue here that certain pieces (atomic clusters) of the atomic active condensed matter may act like neurons. We have just seen that they can establish and break bonds with one another. Additionally, these pieces (active agents) stimulate one another and exchange signals. Indeed, the active agents produce ordered atomic reconstructions of the matter. Those carry complex information and may be absorbed by other agents. The generation and assimilation of the atomic reconstructions changes the intentions of the recipient active agents. In particular, assimilation of an atomic reconstruction may excite the active agents and make them produce further actions, producing all sorts of feedback loops.

In a consolidated condensed body, all the atomic reconstructions mix and form the collective reconstruction (signal), and this collective signal contains multiple interconnected components. The collective signal, together with the participating active agents, forms the collective agent that occupies the entire volume of the condensed body.

It would seem that the active reconstructions of molecular machines and those of neural matter might be equivalent. I assert that the neural matter simply emulates the voluntary actions of the molecular active matter; that is, the subcellular active macromolecules are the prototypes of the neural matter of the brain. Both kinds of active matter do essentially the same thing—they generate autonomous reconstructions—but they do that with different "hardware" and at a different level of complexity. Neural matter is more complex and produces superior reconstructions. However, in simple live artificial beings, the neural condensed matter can be replaced by active condensed matter made of atoms.

20 Ordering and disentanglement of entangled matter through active reconstructions

Disordered (entangled) matter cannot produce organized atomic reconstructions or carry meaningful signals. In entangled matter, the ordered atomic motions produced by active agents will be transformed into thermal noise. To perform considerable autonomous reconstructions, the atomic condensed matter must be orderly arranged. It is desirable that the ordered body be segmented by the easy-tear lines. Then, during reconstruction, the body will separate predictably, into less connected pieces that easily slide along one another.

For a macroscopic manufacturer, the exact manipulations of separate atoms presents a significant challenge. For this reason, atomic condensed matter obtained artificially, without any biological templates, will be disordered, entangled, and motionless.

Section 16 suggested that entangled condensed matter may be arranged and ordered (disentangled) after manufacturing. This possibility was also demonstrated in Part 1 of this paper, using the example of an hourglass. There, the disordered, jammed granular medium was rearranged by the active stream of grains. Generally, the entangled matter gets disentangled by the active, ordered "seed organism" implanted in its body; matter will gradually become reorganized by the repeatable and ordered reconstructions of this organism.

The entangled matter must contain plenty of potential active agents. Those should be activated by the seed organism. This requirement means that the matter must be prone to either condensation or decondensation. For example, the granular matter of the hourglass was prone to decondensation. Its disentanglement corresponded to accumulation and ordering of "decondensates" (voids). Active matter made of atoms must have analogous capabilities.

Fig. 10 illustrates the process of disentanglement of matter prone to decondensation. The entangled condensed matter is implanted with multiple active seed organisms. Every seed organism rearranges its own part of the matter, drags it, and involves it in its own ordered motions. The volumes of the organisms grow.

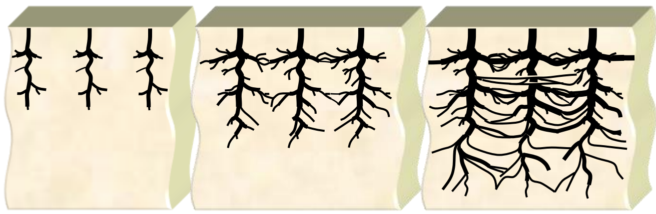

Fig. 10. Disentanglement of the condensed matter made of atoms. The seed organisms (originally independent reconstructions) resemble streams in the hourglass. They must rip and penetrate the matter, connect to one another, and create a common reconstruction.

During the disentanglement of the matter, initially independent organisms connect. At this very moment, they assume the role of neurons. They must create a common evolving reconstruction. One could apply the discussion in

Sections 1 to 17 to these quasi neurons and repeat the reasoning without any modifications. After the active agents succeed in creating the collective organism, further disentanglement is done by the collective reconstruction.

21 Breathing life into condensed matter

To obtain active condensed matter, one needs to take a piece of regular, equilibrated condensed matter and populate it with active agents. Loading condensed matter with real chemical precursors and obtaining self-sustaining chemical reactions would produce real biological specimens. This task is difficult in practice; one would need to find matching reactions and invent means of delivery for the chemicals. However, animation of the condensed body also could be accomplished in a much easier way. The energy to actuate the agents could come from external sources, as it is done in neural networks. Just as the life-support system is not the part of the neural network, so too will our animate condensed matter live on external life support.

The prospective condensed matter must be partially ordered. This will ensure meaningful communications among the agents. But the condensed matter also must remain strongly constrained and entangled. The majority of the active agents must remain inhibited. Moreover, the active agents must be able to rupture the condensed matter; this is the critical requirement, because the experimenter intends to reproduce the autonomous rupturing effect. The condensed matter must be able to fill holes, heal tears, and return to the quiet state. The condensed matter also must memorize the ruptures—that is, the healed tears must differ from the original, untorn material. The prospective experimental system is illustrated in Fig. 11.

A condensed matter bar gets stamped with an array of small, precisely shaped punch stamps. Every punch stamp embosses a certain relief pattern on the bar. The punch stamps emulate the active agents that reshape their environment in an orderly fashion. Pressing on the punch stamp creates a system of internal tears and generates ruptures and controlled reconstructions of the matter. The condensed matter must be able to partially recuperate after removing the load; the embossed relief must fade away and the tears should get healed. The stamping must be periodically repeated to continue actuation of the matter. Repetitive stamping causes the system of healing ruptures to grow in size and complexity.

The cyclic plastic deformations create additional intrinsic active elements in the condensed matter: bond failures, active ruptures, propagating structural faults, and so forth. These become ordered and arranged into patterns around the punch stamps. Roughly speaking, every such pattern corresponds to a neuron. The punch stamps should be placed at a certain separation from one another, then the "neurons" will first grow independently and then interpenetrate, intertwine, and unite into a single network. All the neurons unite into the collective active agent.

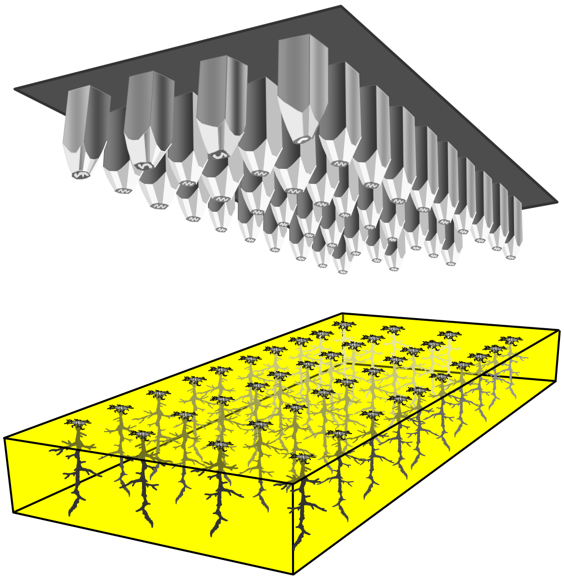

Fig. 11. Schematic representation of active matter driven by punch stamps.

Through this procedure, one would get a well-structured, well-trained, large "substitute" for the neural network, which recognizes complex external signals and generates responses to those signals. An experimenter may want to divide the driving punch stamps (the sources of plastic deformations) into two groups. The first group would emulate the periodic excitation of the neurons and generate the internal activity of the condensed matter. The second group would correspond to the signals that come from the sense organs. Then the active matter would react to varying external stimuli.

22 The realized material embodiment

It turns out that both the material system and the experimental apparatus for populating it with active agents already exist. The condensed matter bodies are CD-RW (rewritable) discs, and the experimental apparatus is the standard CD-ROM drive (Fig. 12).

CD-RW discs are used for repetitive recordings of digital data. During a recording, a very strong and focused laser beam produces an array of "burn pits" on the grooved surface of the disc.

The disc is composed of polycarbonate plastic, coated with a special alloy thin film that absorbs the laser radiation and changes its optical properties, producing the readable burn mark.

The recording inflicts strong heating and localized plastic deformations on the body of the polycarbonate disc. Therefore, every burn pit may be used in the same way as a punch stamp.

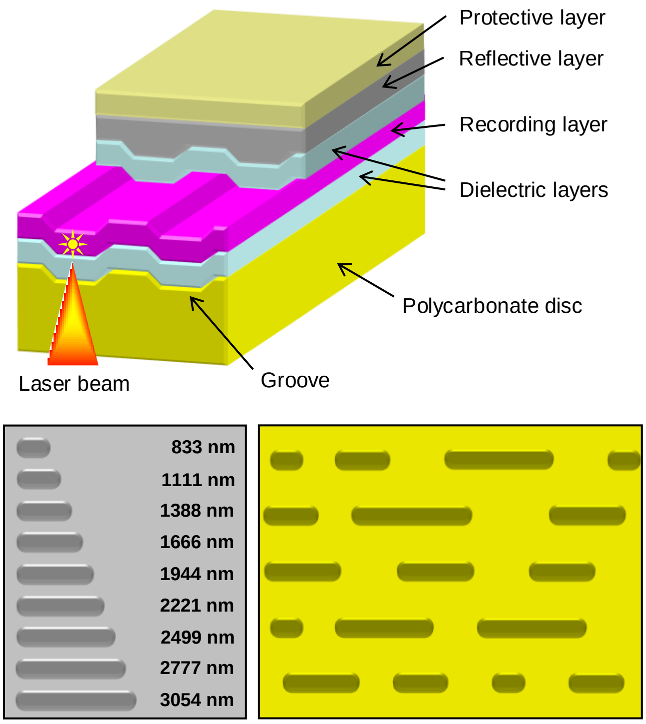

Fig. 12. Top: Structure of the CD-RW disc. Bottom: Burn pits produced by the laser during the data recording.

Altogether, the spiraling track of the disc contains about 10^9 burn pits of nine different lengths (nine different types of stamped patterns, or nine different types of neurons). There are also spaces of nine different lengths between the burn pits. (The information on the CD is actually coded in these lengths.) These can produce a mind-boggling number of different combinations. CD-ROMs are very precise: in the repeated recordings of the same "disc image," the same burn pits hit exactly the same spots (under identical recording conditions). Therefore, one can repeat the stamping of the same places of the disc with exactly the same patterns, and make it periodic.

Multiple recordings cause structural degradation of the discs. These structural modifications manifest themselves as misread burn pits—recording errors—which are detected by the same laser in the low-power reading mode. The error pattern becomes the *post factum* indicator of the reconstructions that took place in the disc during the recording. They could also be regarded as a documented "response" of the condensed matter to the active stimuli. The reading errors appear after several hundreds of recordings. Their number steadily increases until about one thousand recording cycles. Then the experiments suddenly stop as the discs become unreadable.

23 Experimental results and discussion

The active condensed matter on CD-RW discs is fabricated by repeated recordings of the same disc image. This treatment implies that an invariable set of punch stamps emboss the disc, one after another, in a precise sequence.

When the first recording errors appear, they are chaotically distributed across the disc surface. However, as their density grows, they quickly agglomerate in patches of several millimeters across. As the number of recordings increases, these isolated patches expand, move, and gather into larger patches. It appears as if the recording errors engage in "cross talk" and get attracted to one another. They tend to form a single patch or a single segment of the disc. During this process, the other parts of the disc get rid of their errors. Further recordings cause expansion of this error-populated segment until it covers almost the full surface of the disc. Shortly after that, the disc becomes unreadable. This effect is demonstrated in Fig. 13.

This experiment was repeated many times, on different discs and CD-ROM drives, using different burn pit patterns. The shapes and the positions of the error agglomerations were different, but the disproportionate distribution of the reading errors and their tendency to agglomerate on some particular segment of the disc was observed in all experiments.

The deviation from evenly distributed damage may be explained as follows. The misread burn pits might reveal the current position of the collective "rupture." They might indicate the softest, least constrained region on the disc, where most of the activity is concentrated.

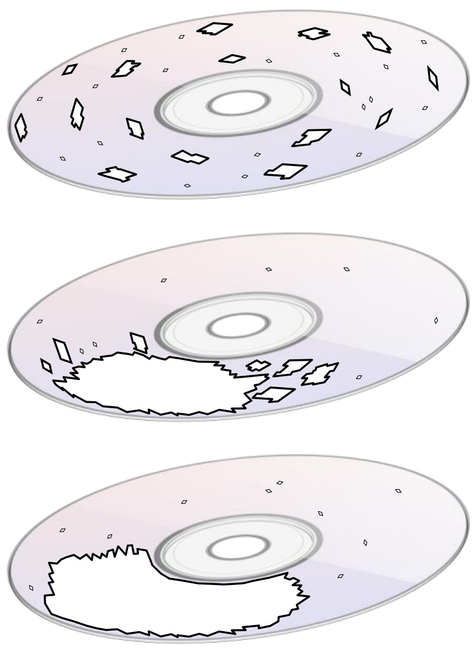

Fig. 13. Bunching of the reading errors on a particular segment of the disc. The size of the segment grows with the number of recordings.

If this supposition is correct, then the experiment reveals how the initially isolated ruptures unite. The initially disagreeing "organisms" communicate and form a single coordinated organism. In this case, the whole disc may be

regarded as a single active condensed matter body. It can produce a single coordinated macroscopic reconstruction. Considering the size of the disc, this reconstruction might become very complex.

This supposition is substantiated by the following observation: if the experimenter starts writing a completely new disc image, the segment almost completely disappears. The distribution of the reading errors becomes almost chaotic. Then, after about one hundred burn cycles, the reading errors attempt to gather again and to create a new segment in a different location on the disc. Sometimes they are successful, sometimes only in some measure. This depends on the quality of the disc and the number of reading cycles it can withstand before becoming unreadable.

Recording of the new image on the old disc implies that a set of completely new punch stamps has started populating the condensed matter with new tears. They destroy the old collective motion and start replacing it with a completely new one.

If the new burn pit pattern differs only slightly from the original, one may achieve a slight and relatively smooth change in the disc response. Generally, the fraction of the changed burn pits must stay below 2% of the original. Then the retrieved error patterns remain similar to the original ones.

Further results of this experiment will be disclosed elsewhere. Here, they merely illustrate how active condensed matter could be fabricated by expedient means.

Conclusions

This paper, together with Part 1, "The animate organism as an active condensed matter body," outline a physicist's perspective on the nature of life. Many earlier authors also have undertaken this endeavor, employing nonequilibrium thermodynamics [4], theories of self-organization [5], complex systems theories [6], active and soft matter theory [7], evolving networks [8], and other approaches [9,10]. Until now, however, none of these authors has come up with a fully satisfactory theory. The present two papers formulate a new doctrine that should help to make yet another step toward the comprehensive physics of life [11].

Here, the fundamental notion is to employ nonequilibrium active agents [12]. The cornerstone is the conjecture that these agents unite into a constrained condensed matter body. Life corresponds to the autonomous reconstructions of this active condensed matter body. The complexity of life depends on the order and the complexity of the active body. The discipline that should produce an adequate description of the biological phenomena is the study of the dynamics of active condensed matter.

Fundamentally, spontaneously reconstructing condensed matter is described by a colossal number of parameters. A vast number of irreversible events is interlinked, using a vast number of causal relations. In such systems, it is very difficult to reduce the variables. For this reason, the present paper is written in an unusual manner, uncustomary for physicists and mathematicians: it contains no formulas that would establish relations among a limited number of parameters.

I believe that adequate active condensed matter dynamics may be created with the help of archetyping—building simplified working models of condensed matter in which the real (very complex) body is replaced by another (much simpler) active body that performs a reduced number of actions. The model body should consist of simpler active elements. However, it also should function similarly to the actual, biological prototypes. The archetype may be used to understand the principles of operation of biological organisms.

I believe that the major cause of the failure of other theorists to develop the physics of life originates in the erroneous reduction of variables. The existing standard methods yield good results only for those molecular systems that involve unrelated events and produce trivial dynamics of the elements, that is, for gases and chaotic liquids. These methods become inapplicable for the evolution of condensed matter (in which all the events are linked). Nonetheless, scientists have persistently used them, driven by the desire to employ the available mathematical tools.

I emphasize that any attempt to outline the statistical mechanics or the thermodynamics of life before undertaking the dynamics will inevitably lead to failure. On the other hand, correct approaches to the reduction of variables make the statistical analysis of the spontaneously reconstructing condensed matter meaningful and informative. A good example of this success is found in the theory of evolving networks [13]. There, the active agents establish and break links with each other, and do nothing else. Regardless of the oversimplification, this modern branch of statistical mechanics yields important clues about spontaneously reconstructing networks, and I adapted several crucial ideas from this field, particularly the notion of condensation [14].

Another example of the proper reduction of variables is found in population biology [15,16]. Presently, this natural science exemplifies the most advanced quantitative description of life. I was inspired by this science as well. In particular, I assimilated some of its terminology, such as "competition," "cooperation," and the like.

Statement of intentions

My intention is to create the theory of autonomous biotic motion and build the first absolutely artificial animate beings. I have described my master plan and revealed the agenda for my future actions.

The goal must be approached from two different directions, building both theoretical and experimental workbenches. Creating the theoretical workbench implies elaboration of the theoretical models of active condensed matter, followed by their computer simulations. Building the experimental workbench requires real material embodiments of the active condensed matter. These efforts must be carried

out in tandem. They should feed each other with information and stimulate each other's development.

For these endeavors, I seek material funding. I also am reaching out to interested enthusiasts, asking for their involvement and participation. Without external help, I will be unable to proceed from speculation and conjecture to solid proof and experimental demonstrations.

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